High Rate
(Precision *and Otherwise*)
Experiments at a Neutrino Factory

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Workshop on The Physics Opportunities of a Neutrino Factory
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Outline

1. What Role does Near-Detector Physics Play at a Neutrino Factory?
2. Anatomy of a High Rate Neutrino Factory Experiment
3. Examples:
   - Illumination by Neutrinos
   - By-Products of Neutrinos
   - Interactions of Neutrinos
4. Conclusions

The Role of High Rate Experiments

Near detector physics will not drive the design or construction of a neutrino factory

So why is this important?

- A neutrino factory is likely to be a $\gtrsim 10^9$ CHF machine.

  FNAL Main Injector < Neutrino Factory ≪ Linear Collider

- Opportunity cost of building a neutrino factory may therefore be several incremental programs at existing facilities

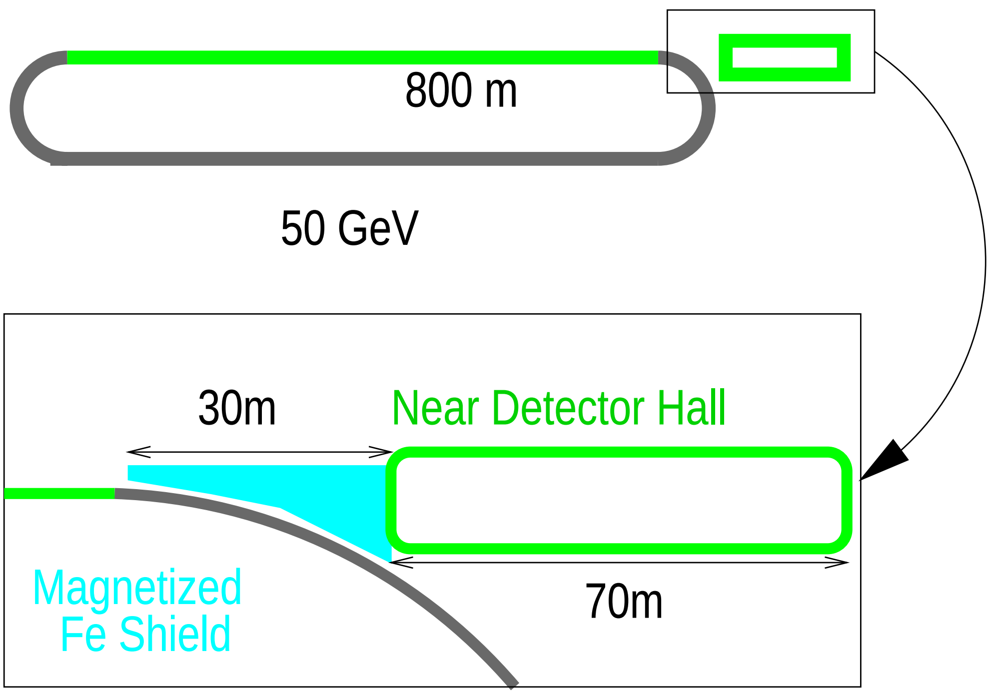
- We are therefore obligated to consider whether such a facility serves a broad range of investigations

And does it pass this test?

- Highly intense beams not only contend with $1/L^2$, but also defeat $G_F s$.
  - ▷ Light targets
  - ▷ High rate production
  - ▷ Rare processes
- In each case, interesting physics opportunities present themselves

The Opportunities

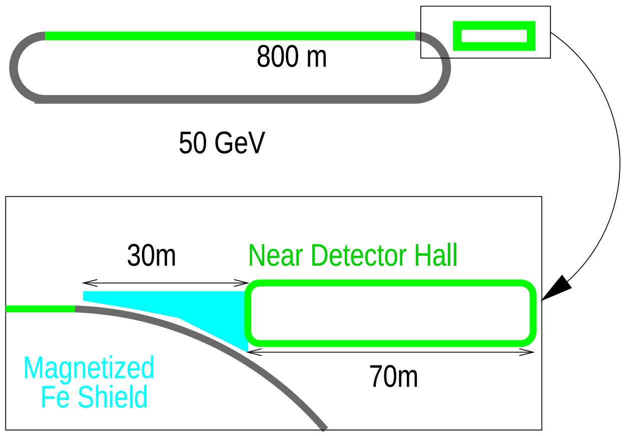
10^{20}/yr μ decays in the green straight section $\Rightarrow$
5–8% of all interactions in detector 10 cm in radius
40–50% of all interactions in detector 50 cm in radius
$\approx 1.5\text{–}3 \times 10^6 \times \frac{E_\mu}{50\ \text{GeV}}$/kg/yr at beam center
(FNAL Neutrino Factory Study Group Parameters)

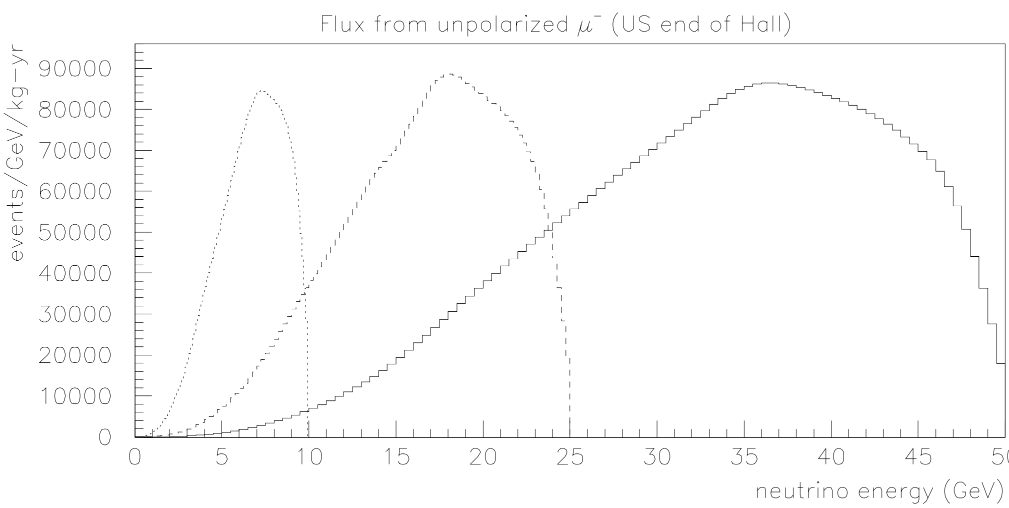


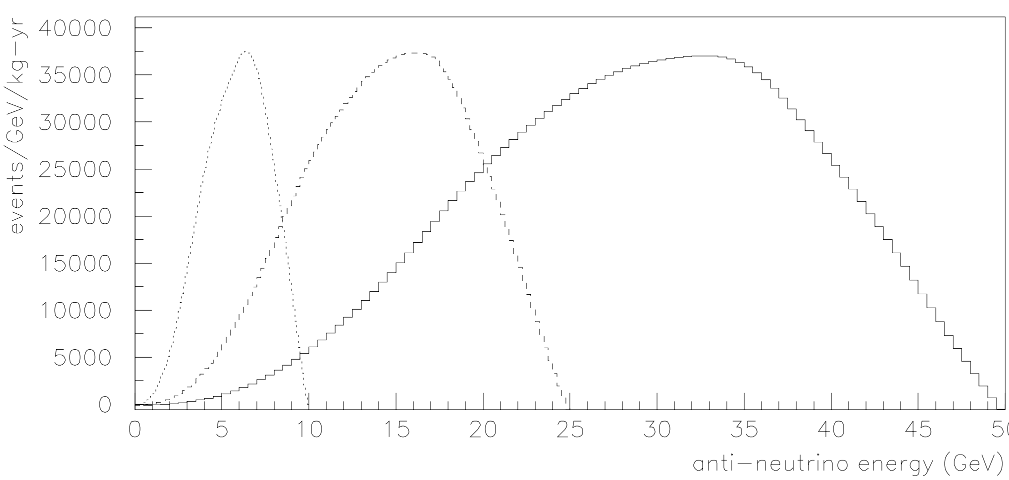
c.f.: Competing facilties

Beam	$\langle E_\nu \rangle$ [GeV]	ν per year
NuTeV/CCFR (Fermilab)	100	$\sim 10^{14}/\text{m}^2$
CHORUS/NOMAD (CERN)	30	$\sim 3 \times 10^{15}/\text{m}^2$
MINOS Near (Fermilab)	15	$\sim 10^{17}/\text{m}^2$
Neutrino Factory	30	$5 \sim 10^{19}/\text{m}^2$

Fluxes

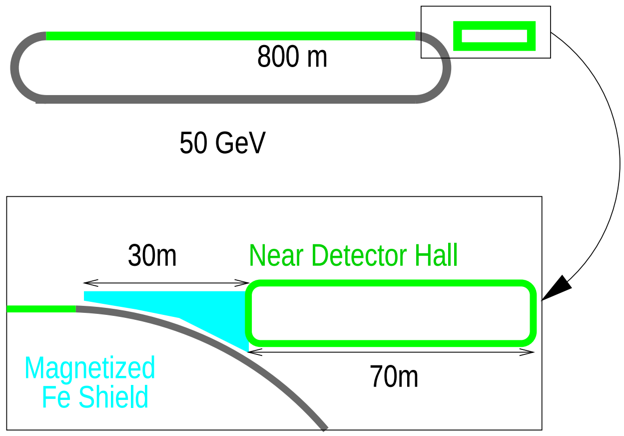


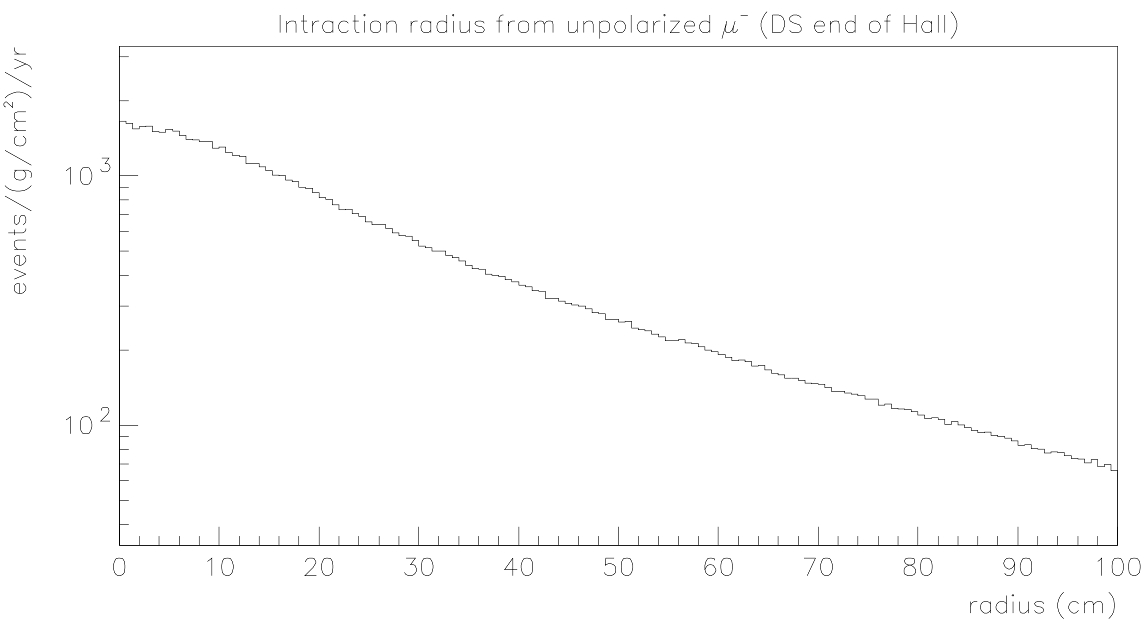




(50, 25, 10 GeV beams shown)

Fluxes II

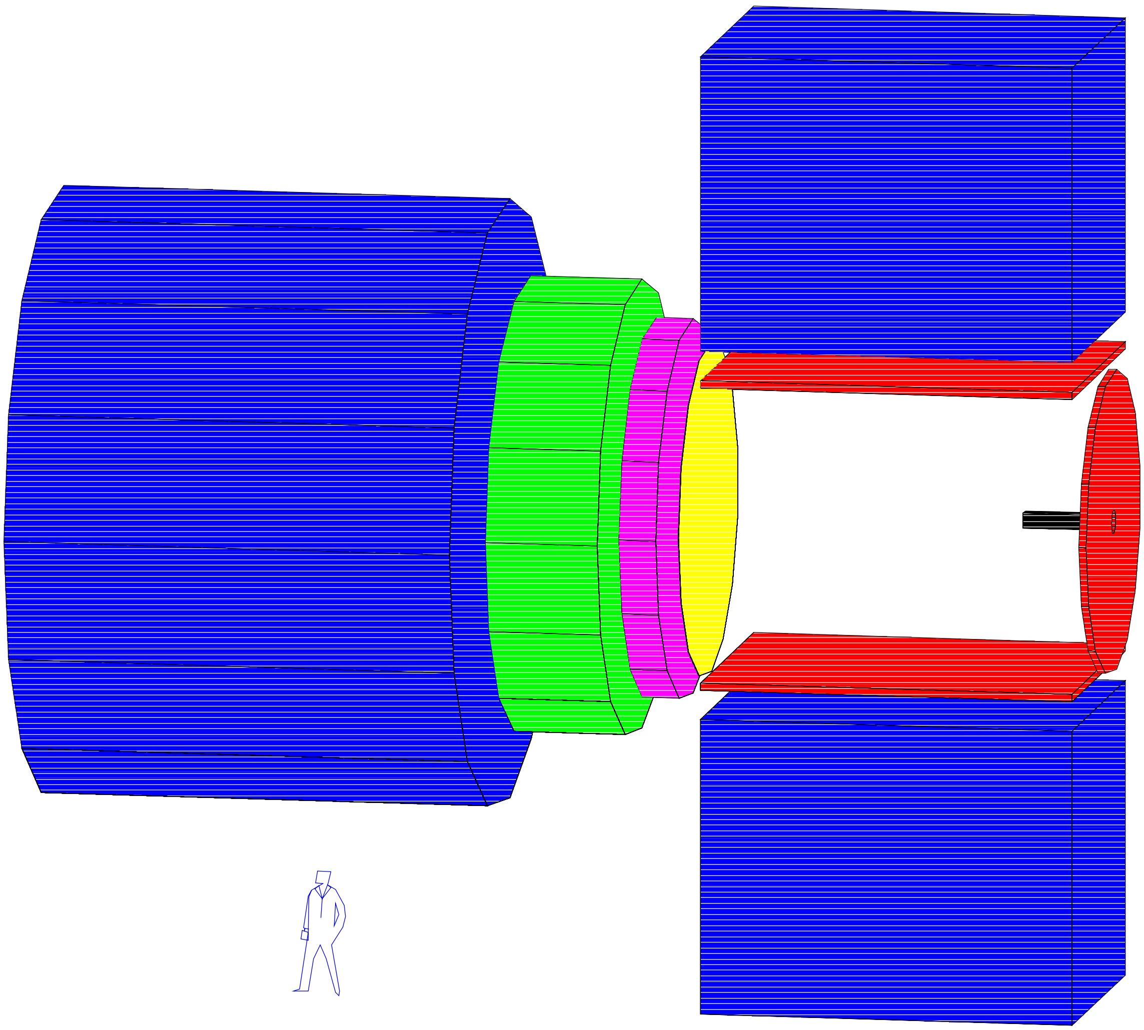




ν radial distribution for 50 GeV muon beam

$$\frac{1}{\gamma} \approx 500$$

Neutrino Detectors??



(multi-purpose detector design of B. King)

Small targets open up new possibilities in

- Target material
- Final state detection

Why Detect Neutrino Interactions?

The properties of the neutrino make it a wonderful laboratory for searching for new physics

…because backgrounds from neutrino interactions are small!

- Weak Interaction is featured
- Clean probe of hadron structure
- Rare ν processes

Nucleon Structure at a Neutrino Factory: Illumination

Why use neutrinos to probe nucleon structure?

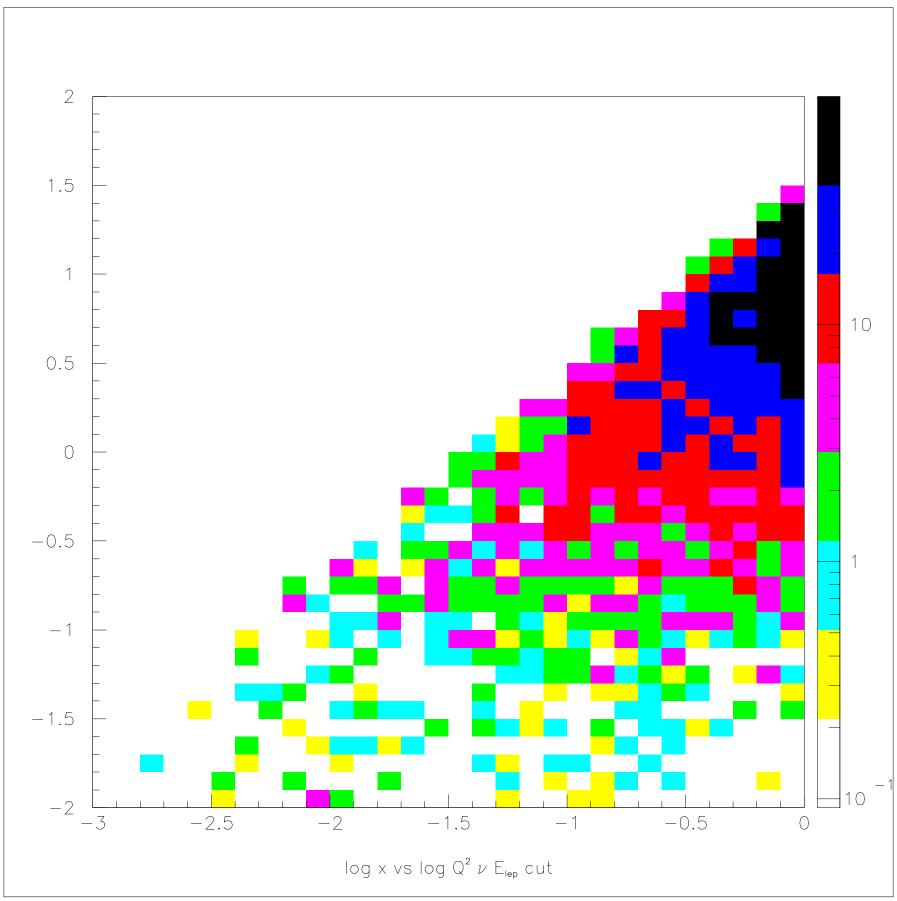
- xF_3
  - ▷ Separation of sea and valence
    - ∗ Fundamental for dynamical models
    - ∗ Evolution to high Q^2 (LHC)
  - ▷ Nuclear effects in xF_3?
- Polarization of Beam
  - ▷ Can't do better
  - ▷ Polarized targets?
- Flavor tagging
  - ▷ $\nu s \to \mu^- c$, $c \to X\ell\nu$ tags strange quarks
  - ▷ $\nu d \to \mu^- u$ but $\overline{\nu} u \to d\mu^+$
  - ▷ $\nu c \to \nu^- c$, $c \to X\ell\nu$ (? hard...)
- High rate means we can wean νN from its addiction to isoscalar targets
  - ▷ Can finally take advantage of the above!

The Deal with the Devil

A neutrino factory solves the rate problem . . .

. . . but high energy may be far away

20 GeV μ Beam



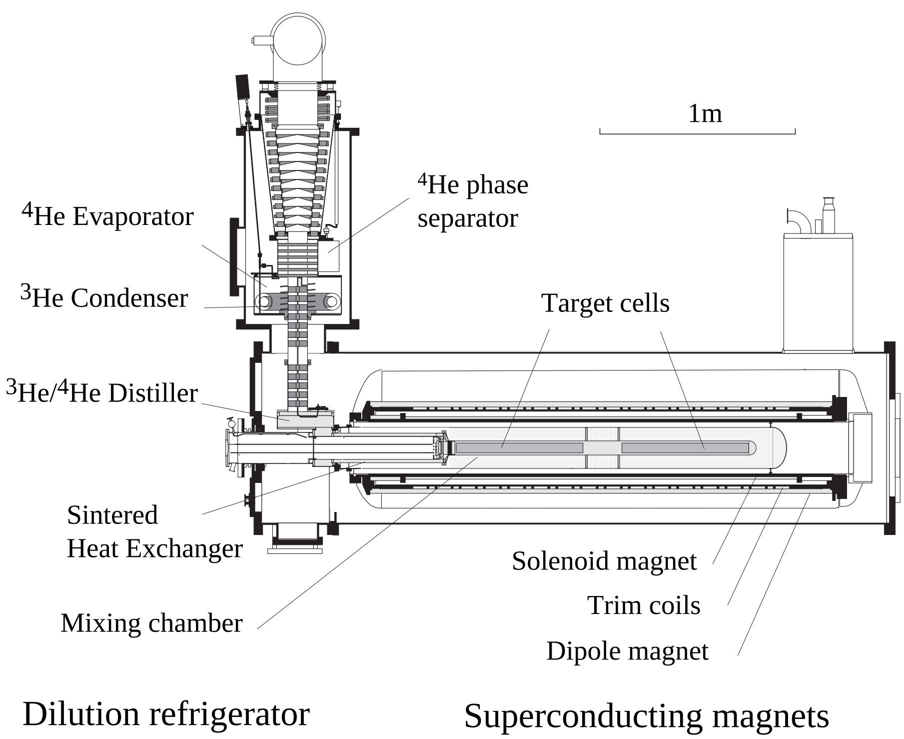
- Can't go as low in x as one might like for sum rules

Polarized Targets

(D. Harris, KSM)

Proof of principle: SMC target

- Solid Butanol ($CH_3(CH_2)_3OH$) target
- Two cells 60cm long, 5cm diameter: $2 \times 1.42\,\mathrm{kg}$ each
- 2.5T B Field, 1K 100% polarized electrons
- Dilution factor: f=0.1 (SMC, `hep-ex/9702005`)



Imagine a 120 kg (1.5 m long, 20 cm radius) Target:
is this crazy?

Polarized Targets (cont'd)

(D. Harris, KSM)

Goal: Flavor-Separated Spin

$$\nu u \to \ell^- d \qquad \nu\overline{d} \to \ell^- \overline{u}$$
$$\overline{\nu} d \to \ell^+ u \qquad \overline{\nu}\overline{u} \to \ell^+ \overline{d}$$
$$\overline{\nu} s \to \ell^+ c \qquad \nu\overline{s} \to \ell^- \overline{c}$$

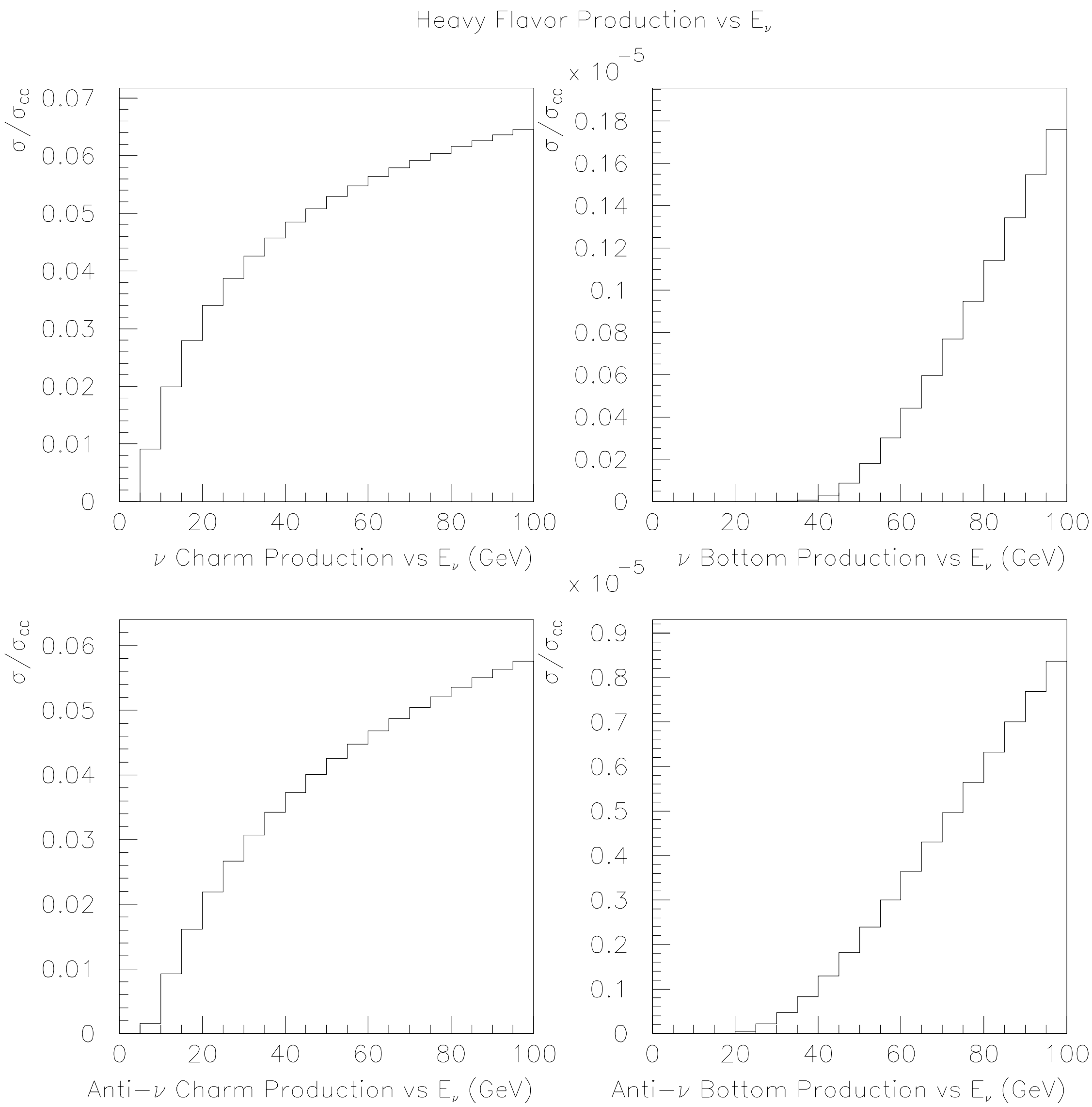
- q and $\overline{q}$ from the inelasticity distributions
- $\nu/\overline{\nu}$ from lepton flavor

$\overline{\nu}(\nu)s(\overline{s}) \to \mu^{\pm}c(\overline{c})$ separated from $c \to \ell\nu X$ final states ($\sim$ 1% of cross-section at 50 GeV)

$\Rightarrow$ Measure strange sea polarization to $\sim$ 1% precision (one year)

- Vastly superior flavor separation compared to hadron-based separation in HERMES

Neutrino Charm Factory: By-Products



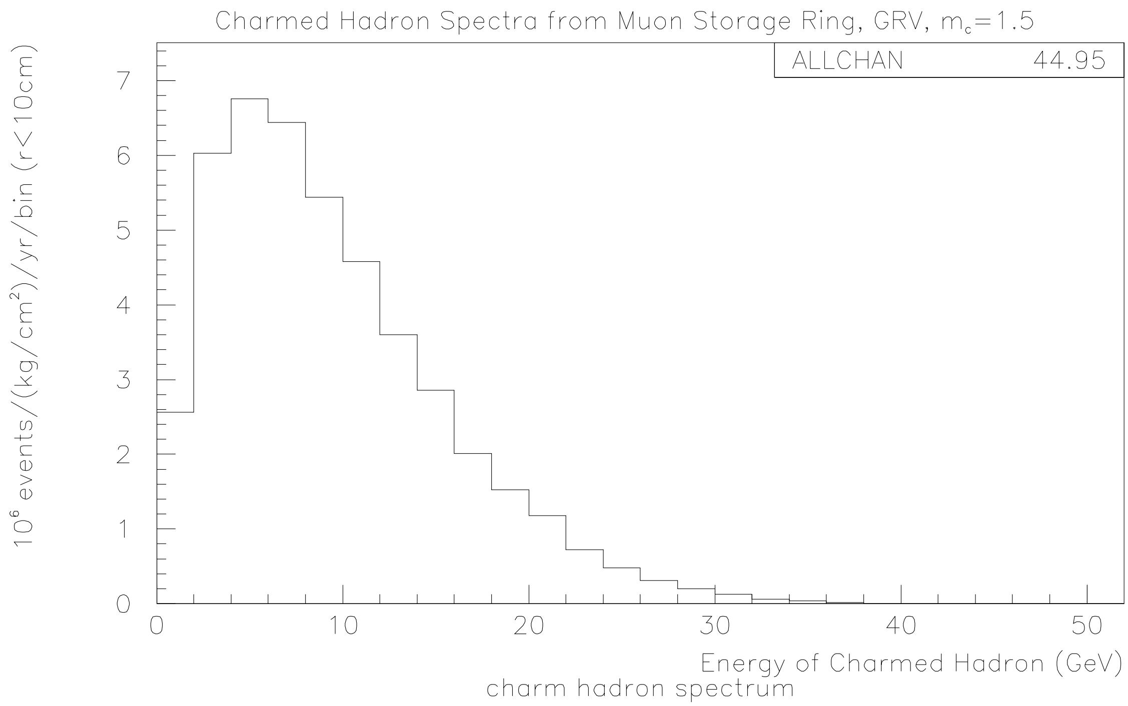
$$\frac{\sigma_{\text{charm}}}{\sigma_{\text{CC}}} \qquad\qquad \frac{\sigma_{\text{bottom}}}{\sigma_{\text{CC}}}$$

- Charm Production averages $\approx 3\%$ of cross-section
- Bottom Production not accessible at 50 GeV

  ▷ precise measure of $|V_{ub}|$ at high E_ν? (B. King)

Neutrino Charm Factory II

- Charm spectrum is soft by fixed target standards
- Still, 10^5/kg-yr charmed hadrons above 10 GeV



charm hadron spectrum

- Rate is high; non-charm backgrounds relatively low
- Tagging
  - ▷ $\nu\, s \to \ell^- c$
  - ▷ $\overline{\nu}\, \overline{s} \to \ell^+ \overline{c}$
  - ▷ Tagging backgrounds are typically very low
    - ∗ Most common mistag from $c \to \ell^+ X \nu$ (benign since charm is misreconstructed also)
- So what to do with $\sim 10^8$ tagged charm?

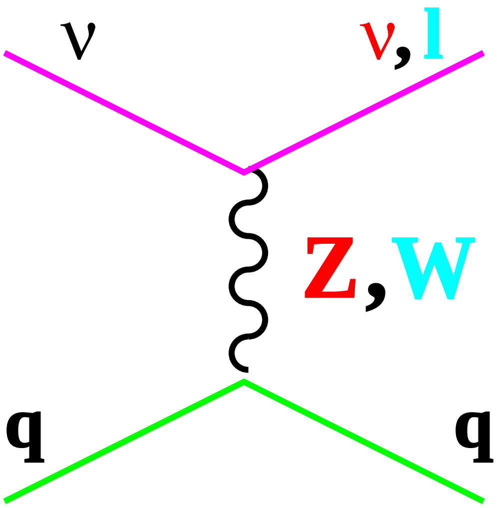
$D^0 - \overline{D}^0$ Mixing

- $D^0 - \overline{D}^0$ is a clean signature of new physics if seen above 10^{-6} level
- e^+e^- and Fixed Target currently at few$\times 10^{-3}$ level (BaBar estimates few10^{-4} sensitivity with years at design luminosity)
  - ▷ Stuck on systematics/backgrounds
  - ▷ Reconstructed flavor from $D^0 \to K^-\pi^+$ (but $D^0 \to K^+\pi^-$ is 1% of this rate)
  - ▷ Proper lifetime analysis required to get below 10^{-2}

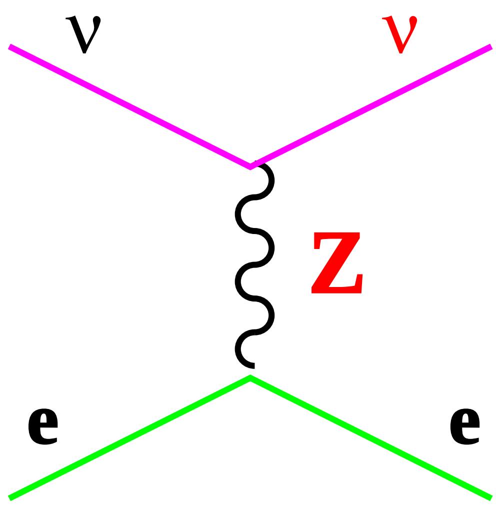
One idea for $D^0 - \overline{D}^0$ Mixing in a Neutrino Factory Beam:

- High momentum lepton is tag
- Measure (inclusive) second lepton charge
  - ▷ about 30% from neutral D mesons
  - ▷ 10% efficient, assuming only $e^\pm$ useful
    - ∗ There is a few$\times 10^{-2}$ background from light meson decays in showers for the case of muons
  - ▷ probe 5×10^6 D^0 decays
- $D^0 - \overline{D}^0$ mixing gives $\ell^\pm_{\rm tag}\ell_{\rm charm^\pm}$
  - ▷ vs dominant $\ell^\pm_{\rm tag}\ell^\mp_{\rm charm}$

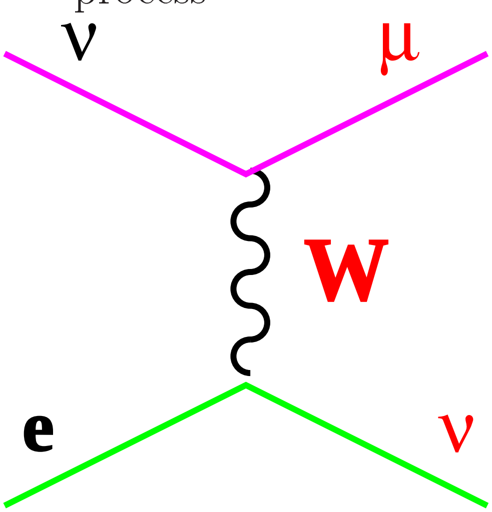
Probes of Weak Interactions: Processes



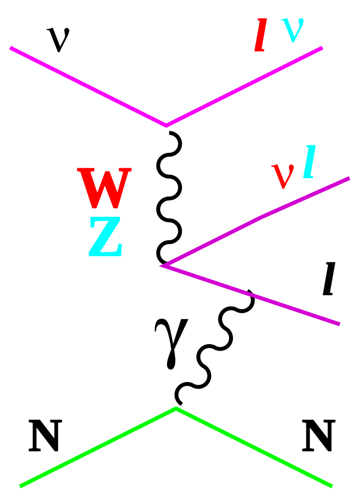
- High statistics
- Needs high energy
- Traditional (low rate) process



- Possible at low energy
- Low rate
- Normalization problem

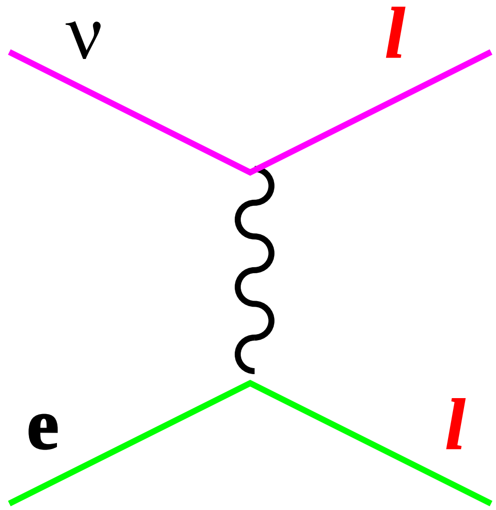


- Low rate
- Backgrounds



- W-Z interference
- But N is a problem

Neutrino-Electron Scattering



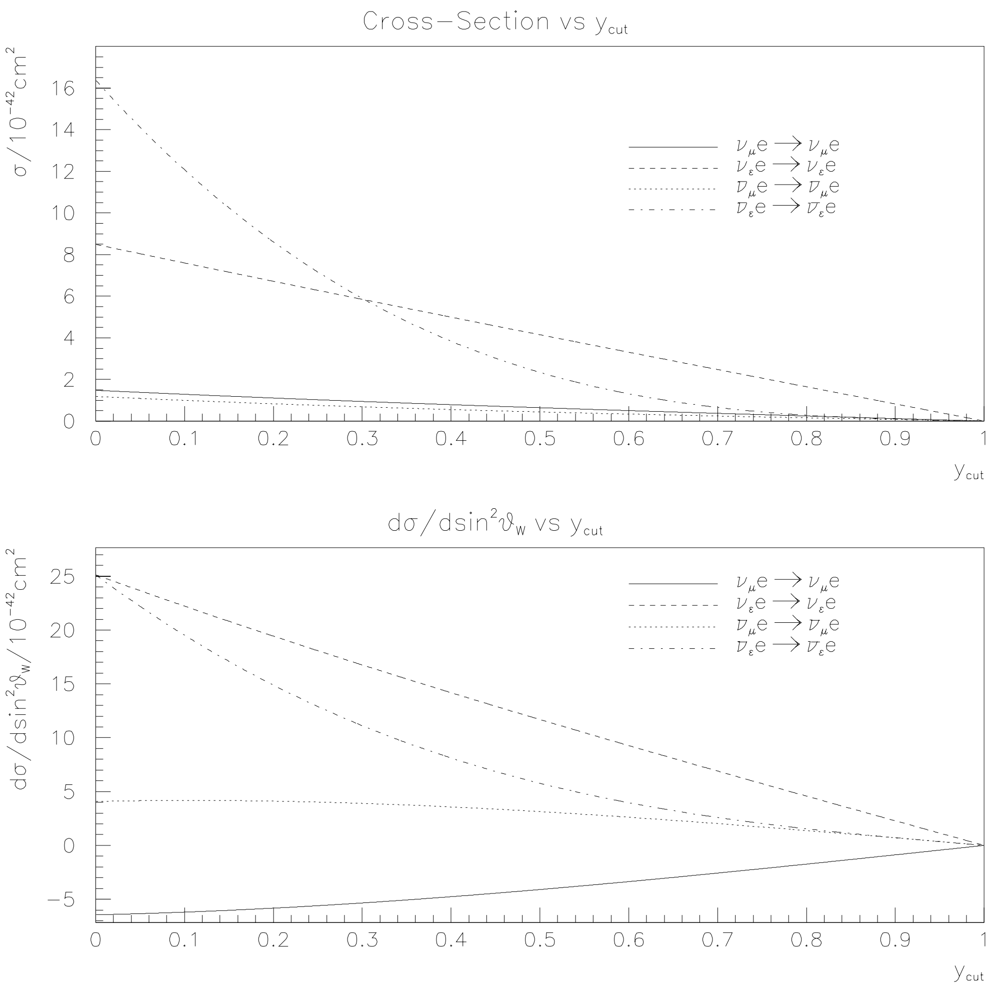
$\nu_\mu e^- \to \nu_\mu e^-$	NC only
$\nu_\mu e^- \to \nu_e \mu^-$	CC only ("inverse muon decay")
$\overline{\nu_\mu} e^- \to \overline{\nu_\mu} e^-$	NC only
$\nu_e e^- \to \nu_e e^-$	NC and CC
$\overline{\nu_e} e^- \to \overline{\nu_e} e^-$	NC and CC
$\overline{\nu_e} e^- \to \overline{\nu_\mu} \mu^-, \overline{\nu_\tau} \tau^-, \overline{u} d \ldots$	s-channel annihilation

Why are these interesting?

- Target is a point particle: well-predicted cross-section
- NC processes sensitive to new physics ($\nu\nu ee$ coupling)

Neutrino-Electron Scattering (normalization)

$\sigma(E_\nu = 1\ GeV)$

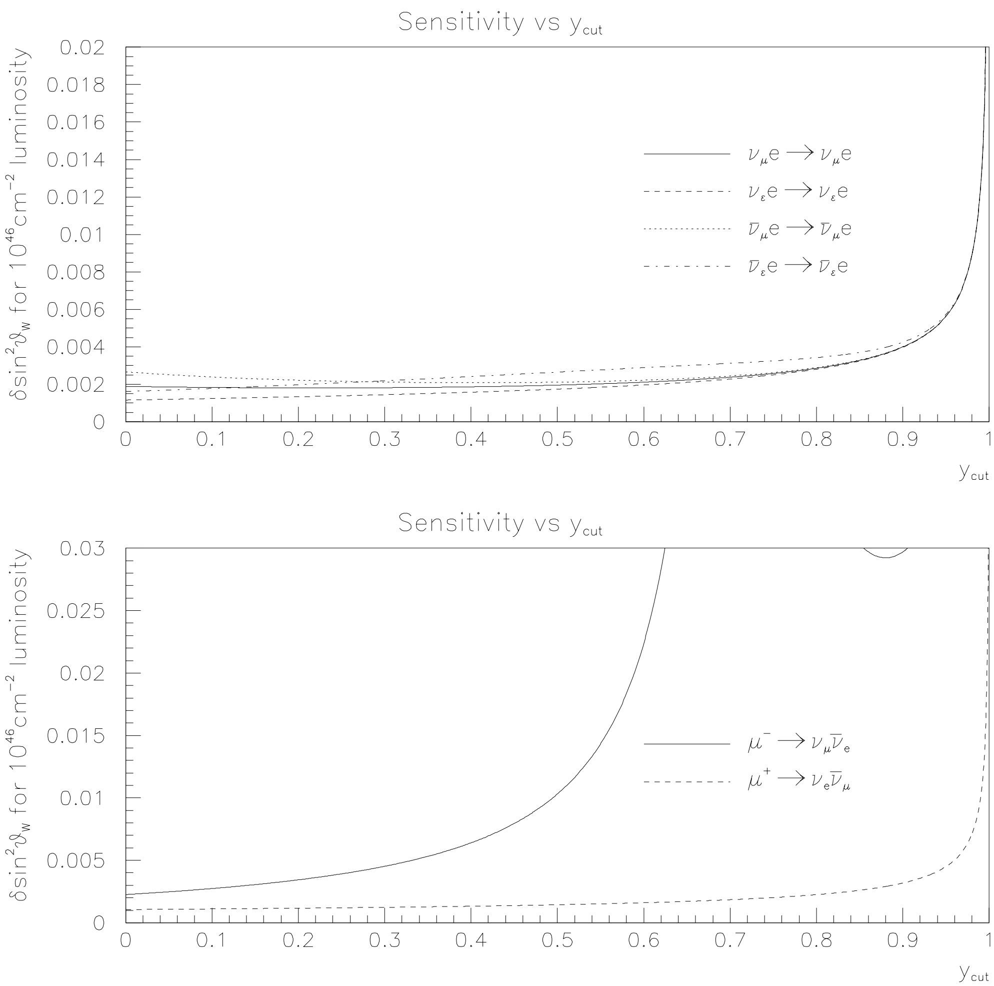


- CC-only process in μ^- beam (IMD) easy to normalize
- μ^+ beam, $\nu_e e \to \nu_e e$ varies by 0.1% for $\delta \sin^2\theta_W \sim 0.0005$
- Part per mil normalization available for 400 kg-yr

Neutrino-Electron Scattering ($\sin^2\theta_W$)

(B. King, J. Yu, KSM)

For 1 GeV neutrinos,

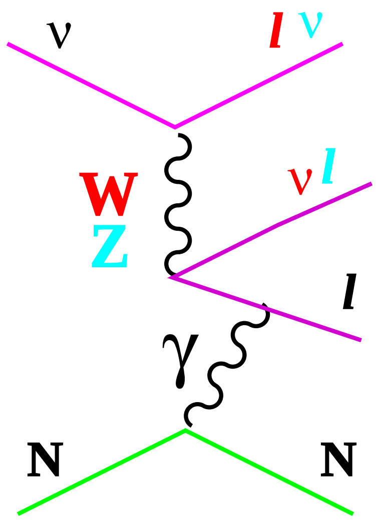


(10^{46} cm^{-2} is 20 kg of material in beam)

- Reasonable to imagine $\delta\sin^2\theta_W$(stat)$\sim$ 0.00002$-$0.00004 (2000kg-yr)
- μ^- beam easy to normalize (IMD) but less sensitive

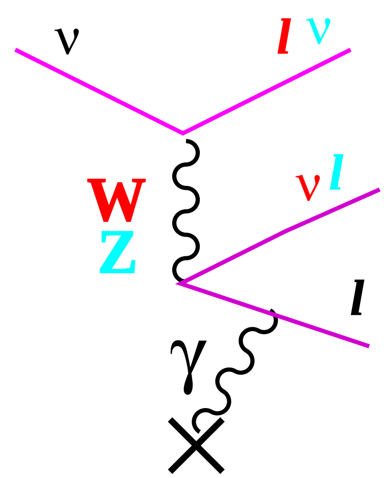
"External Tridents"

(A. Melissinos, KSM)



Nuclear form-factor leads to a large uncertainty in the cross-section

External field!
(well-determined, but weaker)



$$\sigma_{\nu\gamma} = \frac{\alpha G_F^2 s}{9\pi^2} \log \frac{s}{s_{\min}}$$

"External Tridents" (cont'd)

(A. Melissinos, KSM)

In an external magnetic field:

$$P_{\ell^+\ell^-} = \frac{\alpha G_F^2 s}{9\pi^2} \log \frac{s}{(2m_e)^2} \frac{B^2 E_\nu}{2m_\ell^2} l$$

For a 2 T, 10 m long field 20 cm in radius (50 GeV μ beam),

$$N_{e^+e^-} \sim 3 \times 10^3/\mathrm{yr}$$
$$N_{\mu^+\mu^-} \sim 0.03/\mathrm{yr}$$

- Signal is low mass, forward e^+e^- pairs from external field and nothing else
- High rate
- Needs a ν_e or $\overline{\nu}_e$ beam to test interference of W/Z terms (T. Bolton)
- Sensitive to anomolous $W\gamma$ or $Z\gamma$ couplings(?)

Direct Probes of Neutrino Properties

Some of the laundry list:

- Charge radius $< r^2 >$ as an elastic form-factor or radiative emission
- Decays of heavy neutrinos with $m_{L^0} \sim 50$ MeV
  $m_{L^0} \rightarrow e^+e^-\nu$
- Interaction/modification of ν beam in high external field
- ...

Why persue these at a neutrino factory?

- Roughly 10^4 increase in available neutrino fluxes

Conclusions

1. Short Baseline Physics is an important part of a neutrino factory
   - Neutrino "facility" for many different types of physics
   - Unique capabilities to probe strong, weak interactions
2. Near detector lab crucial for long baseline measurements
   - Flux, cross-sections, testbeam
3. Like the long baseline frontier, this rate of neutrinos in another unexplored opportunity
   - May yield surprises!